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Prevention of disease in ferrets fed an inactivated whole cell *Campylobacter jejuni* vaccine

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Abstract

Ferrets were used to demonstrate the potential of a killed whole cell vaccine prepared from *Campylobacter jejuni* to protect against disease. *C. jejuni* strain 81–176 was grown in BHI broth, formalin-fixed, and resuspended in PBS to a concentration of 10^{10} cells per ml. This vaccine (CWC) or live organisms were delivered orally with a nasogastric tube into anesthetized animals treated to reduce gastric acidity and intestinal motility. When 5×10^{10} CFU of the vaccine strain (Lior serotype 5) or one of two other serotypes, CGL-7 (Lior 4) or BT44 (Lior 9), was used to challenge the ferrets, all of the animals developed a mucoid diarrhea. If the animals had been challenged with 5×10^9 CFU of the homologous strain 1 month before challenge with 10^{10} CFU, 80–100% protection against disease was seen. This protection was also obtained after an initial exposure to the 81–176 strain followed by challenge with either of the heterologous strains. CWC was used to see if protection demonstrated with the live organisms could be produced with the non-living preparation. When 10^9 cells of CWC was given as two doses 7 days apart with or without 25 μg of a coadministered mucosal adjuvant, LT_{R192G}, only 40–60% of the animals were protected. If the regimen was changed to four doses given 48 h apart, 80% of the animals were free of diarrhea after subsequent challenge. Increasing the number of cells in the four dose regimen to 10^{10} cells did not improve protection. Animals given four doses of 10^{10} cells combined with LT_{R192G} were subsequently challenged with 10^{10} cells of the homologous strain or the heterologous strain CGL-7. The CWC protected against both strains. Serum IgG antibody titers determined by ELISA showed little increase following the CWC four dose vaccination regimen, compared to animals given one dose of the live organism. On subsequent challenge, however, both CWC vaccinated and live-challenged ferrets showed comparable antibody titer increases above those obtained following the initial challenge or vaccination. Western blots were used to show that the immunodominant antigen in vaccinated animals was a 45 kDa protein, while in ferrets challenged with live organisms the immunodominant antigen was a 62 kDa protein. These data show that the CWC can be used to protect against disease caused by *Campylobacter*. They also show that protection and serum IgG responses do not depend upon the use of the mucosal adjuvant and that cross protection among some of the major serotypes of *Campylobacter* responsible for human disease is possible.
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Keywords: *Campylobacter*; Vaccine; Diarrhea

1. Introduction

Campylobacter jejuni is now recognized as a leading cause of foodborne disease in the United States, as well as worldwide [1–4]. It is likely that an effective vaccine can be developed against disease caused by *Campylobacter*. Prospective epidemiological and human challenge studies suggest that protective immunity develops after a prior *C. je-*

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juni infection [4–6]. Human volunteers fed *C. jejuni* become infected and respond with the development of specific serum IgG, IgM, and IgA to *Campylobacter* [6]. In developed countries, a peak incidence of disease is seen in children below 1 year of age and in young adults [7–10]. In developing countries, where campylobacters are hyperendemic, symptomatic disease occurs in young children and persistent carriage occurs in adults without symptomatic disease [11,12]. It appears that a high level of endemic disease (i.e., hyperendemicity) results in the development of specific serum and secretory antibodies and less severe disease [13–15]. Following exposure, specific serum and secretory antibodies develop that provide strain-specific immunity and protection from disease caused by the homologous strain, although recolonization may occur [5,6].

Vaccines have not been developed for use against *Campylobacter*. Orally-administered inactivated whole cell *Campylobacter* vaccines offer a potentially useful approach towards immunization against *C. jejuni*. Physically, inactivated organisms are naturally-occurring microparticles that should enhance interactions between the antigens they carry and the mucosal lymphoid tissues. As vaccines, they are safe when given orally and inexpensive to produce and administer. Whole cells possess multiple antigens that can be particularly important to protection, particularly when protective antigens are not known.

When grouped according to a serotyping scheme based on heat labile antigens [16] only about a dozen of the over 100 Lior serotypes are associated with disease in humans. Strain 81–176 of *C. jejuni* was selected to make an inactivated whole cell vaccine since it is one of the clinically important serotypes, Lior 5. Further, this strain has been used in clinical challenge studies [5,6] and does not show mimicry of any gangliosides associated with Guillian Barre syndrome (GBS) (A.P. Moran, personal communication).

An important question is whether a single serotype, such as Lior 5, can protect against disease induced by other clinically important serotypes. Due in part to the difficulty in doing cross serotype protection studies in humans, as well as the problem of trying to be sure no challenge strains may induce GBS, an animal model is needed to show cross-strain protection against disease.

Colonization, rather than disease, models have been used to show that the CWC vaccine does protect against *C. jejuni*. Mice have been orally immunized with a three-dose primary series of particles of CWC (48 h intervals) at doses of 10^5, 10^7, or 10^9 cells [17]. The vaccine was given to mice with or without the mucosal adjuvant consisting of the heat-labile enterotoxin of *Escherichia coli* (LT) [18]. These studies showed that the *Campylobacter*-specific intestinal IgA response was dependent on the use of LT, whereas serum immunoglobulin responses were not. Colonization resistance was induced over a broad range of vaccine doses when LT was included. However, only the highest dose (10^9) of CWC alone gave comparable levels of protection against colonization. Both the adjuvanted and unadjuvanted formulations given at the intermediate dose (10^7) provided equivalent protection against systemic spread of challenge organisms.

Colonization has also been studied in the Removable Intestinal Tie Adult Rabbit Diarrhea, or RITARD, model for *Campylobacter* infection [19]. This model relies on a surgical procedure, in which the challenge organism is introduced into the bowel of immunized and nonimmunized rabbits to model intestinal colonization: no disease is produced in animals old enough to have completed immunization. Protection against colonization was seen when three doses of CWC were given by gavage at weekly intervals [20]. Protection was not obtained in this model if LT was not present. This protection against colonization was Lior serotype specific [16,20].

Ferrets are one of the few animals that develop a *Campylobacter*-induced diarrheal disease similar to that seen in humans [21–23]. Ferrets develop enterocolitis associated with natural *C. jejuni* infection and following experimental inoculation with pure cultures, develop mild to moderate diarrhea characterized by the presence of mucus, fecal leukocytes and blood in the stool. Diarrhea was more severe in younger (6–7 week old) animals than older (11–12 week old) animals, with more fluid stools often accompanied by anorexia for a day or two. Ferrets fed live ferret-derived strains of *Campylobacter* develop an immune response making these animals resistant to disease following a second challenge with the same strain [22]. For both adult and young ferrets, infection and disease occur without any prior manipulation of the animals.

The purpose of the present study was to use the ferret to provide evidence that protection against enteric disease caused by *Campylobacter* could be obtained in a natural host and that this protection might be relatively conserved. Protection against disease was found to be at least somewhat conserved among serotypes of *Campylobacter.* These studies showed, furthermore, that protection against disease was associated with vaccine dose and, in contrast to colonization, was not enhanced by use of adjuvant. Further, following vaccination with the killed preparation, a strong serum immune response was obtained in protected animals with a 45 kDa OMP as the immunodominant antigen.

2. Materials and methods

2.1. Bacterial culture

C. jejuni strain 81–176 (Lior serotype 5) was isolated during a 1981 foodborne outbreak. Strains CGL7 (Lior serotype 4) and BT44 (Lior serotype 9) were isolated during military field exercises in Thailand from the stools of patients with acute diarrhea. Frozen stocks were thawed, inoculated onto tryptic soy blood agar plates and incubated at 42 °C in polybags (Levin Bros Paper Co., Chicago, IL) with an atmosphere of 85%N_2–10% CO_2–5%O_2. Cells were first passed through Mueller Hinton motility agar to confirm colonies remained motile and then plated to Muller Hinton agar. After

18 h of growth, the cells were collected from the plates and suspended in PBS. The cells were then screened for contamination by phase-contrast microscopy and used directly for animal challenge.

2.2. Preparation of whole cell vaccine

The CWC vaccine is a monovalent preparation made up of 2.5×10^{10} particles of *C. jejuni* strain 81–176 per ml. The organism was grown to a concentration of 1×10^{9} CFU per ml by overnight incubation at 37 °C in brain heart infusion (Difco, Detroit, MI) plus 0.1% deoxycholate (Sigma, St. Louis, MO) at 37 °C in a 10% CO_2 and 5% O_2 atmosphere. The broth culture was inoculated with 5 ml of saline rinse from an overnight blood agar plate culture per 400 ml of broth. At the time of harvest the culture was centrifuged and the bacteria resuspended in Hanks Balanced Salt Solution to which formalin was added to a concentration of 0.025 M. After overnight incubation at room temperature, the inactivated bacteria were centrifuged again and concentrated by resuspension in phosphate buffered saline to a concentration of 2.5×10^{10} particles per milliliter. The vaccine was stored at 4 °C. Twenty-five micrograms of the adjuvant LT_{R192G} [18] was used with some vaccine preparations.

2.3. Animal challenge

Six week old female ferrets were purchased (Marshall Farms, N.Y.) and were housed singly in polycarbonate guinea pig cages covered with a filter bonnet top and modified to contain immobilized feed and water pans. A piece of PCV pipe (2 in. o.d.) was added to each cage to provide a nesting area. Animals were provided with Marshall Farms Ferret Chow and reverse deionized water ad libitum and were allowed to acclimate to the housing for at least 48 h prior to being fed any vaccine and at least 1 week prior to being infected with live organisms. During this time animals were observed for any signs of distress and diarrhea. Prior to being shipped by Marshall Farms and during the acclimation period, rectal swabs were taken from each animal and cultured for *C. jejuni*. Any animal found culture positive was removed from the study. This research met the principles set forth in the 1996 edition of the Guide for the Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council, U.S. Department of Health and Human Services and all the protocols and procedures involving the care and use of ferrets were approved by the FDA Center for Food Safety and Applied Nutrition IACUC committee.

For oral gavage of ferrets less than 8 weeks of age, food was withheld for 5–6 h prior to challenge. For animals greater than 8 weeks old, food was withheld for 18 h prior to challenge. Animals received 60 mg/kg of ketamine plus 0.75 mg/kg acepromazine intramuscularly. Following sedation, the vaccine or challenge dose was administered orally via a pediatric nasogastric tube. Care was taken to ensure proper placement of the tube and the animals were closely monitored for any signs of aspiration. After 60 min, animals being fed live organisms were administered 2.8 ml per kg of paragoric (Alpharma, Ft. Lee, NJ) intraperitoneally to slow peristalsis, thus allowing time for a productive infection to proceed. For secondary challenge the procedure was otherwise identical to primary feeding except that a sodium bicarbonate solution (4 g/150 ml) was delivered intragastrically 10 min prior to challenge to reduce stomach acidity. In addition, drinking water was supplemented with tetracycline (1.5 g/l) for three days prior to rechallenge to decrease the competing intestinal microflora. All challenge doses were monitored by plate counts.

Following infection, animals were monitored three times daily for signs of diarrhea, dehydration, appetite and water consumption. Rectal swabs from each ferret were cultured for *C. jejuni* by direct plating on *C. jejuni* selective agar. At the appropriate time, blood samples were obtained by bleeding the animals from the jugular vein while under light anesthesia using acepromazine-ketamine. Collected sera were assayed for specific anti-*Campylobacter* immunoglobulin levels. At the conclusion of each experiment, animals were lightly anaesthetized with acepromazine-ketamine then euthanized by intracardiac injection of sodium pentobarbital.

2.4. Study protocol

On the day of initial feeding, serum samples were taken from all animals and assayed to determine baseline serum anti-campylobacter titers. When animals were re-challenged, serum samples were taken on the day of challenge and 12 days post-challenge. In selected rechallenge studies serum samples were obtained 1 week post initial feeding as well. For primary feeding/immunization studies, ferrets were intragastrically dosed at 6–8 weeks of age with live *C. jejuni* strains or various CWC vaccine regimens. For secondary challenge, ferrets were intragastrically dosed at 11–12 weeks of age. Homologous challenge studies involved oral feeding, followed by oral rechallenge with the same Lior serotype, whereas heterologous challenge studies involved oral feeding and rechallenge with different Lior serotypes. Control animals were either left untreated or intragastrically fed PBS containing *E. coli* heat-labile toxin (LT_{R192G}). Stools were graded on a 0–2+ scale: 0 = normal stool; 1+ = loose stool; 2+ = gross mucus diarrhea. Only animals with 2+ stools were considered to be positive for diarrhea. Initially attempts were made to include additional physiological parameters including body temperature, blood pressure, and fecal leukocytes. These measurements were difficult to obtain and produced inconsistent results. For this reason they were discontinued.

2.5. Immunoassay

Serum IgG titers were determined by indirect ELISA. *C. jejuni* 81–176 whole cells were used as antigen to evaluate strain-specific immune response of the primary antibody in the ferret serum. For IgG immunoassay, horse radish peroxidase (HRP)-labelled goat anti-ferret IgG (H + L) (Kirkegaard & Perry Laboratories, Inc., Gaithersburg, MD) was used at 1/500 as secondary antibody. Nunc-maxisorp 96-well immuno-plates were coated with 100 μl of Campylobacter whole cells (10^9 cells/ml) resuspended in carbonate buffer (pH 9.6) as the primary antigen, then incubated at 37 °C for 1 h before storage at 4 °C overnight. After washing the coated plates three times with PBS-Tween 20 (0.1%), 150–200 μl of blocking buffer (5% of bovine serum albumin in PBS-T20) was added to each well and incubated for 1 h. Plates were washed three times and primary antibody—ferret serum samples in different dilutions were added. After 2 h incubation at 37 °C and five times washing, 100 μl of HRP-conjugated goat anti-ferret IgG (0.2 μg/ml) antiserum were added to each well. Plates were incubated for another 1.5 h and washed five times. A hundred microliters of substrate (ABTs + H_2O_2) was added per well. Immunoglobulin G (IgG) was detected by using UV_{max} microplate reader (Molecular Devices Corp., Sunnyvale CA) at OD_{405}.

2.6. Western blot

Total protein extracts were prepared by sonication of live or formalin-inactivated whole cells. Cell extracts were boiled in sample buffer containing beta mercaptoethanol. The samples were separated on 4–20% SDS–PAGE and transferred to a nitrocellulose membrane by use of a Bio-Rad (Richmond, CA) transblot apparatus. The membranes were blocked with 0.5% BSA + 0.5% casein in PBS for 1 h at room temperature. After this, the membranes were cut into small strips. A 1:100 dilution of mouse serum was added and the membranes held overnight at 4 °C before washing four times with 0.1% PBS-Tween. A goat anti-ferret IgG antibody conjugated with alkaline phosphatase (KPL, Gaithersburg, MD) was applied for 2 h at room temperature. The blots were developed with a Sigma fast red TR.Napthol AS-Mx substrate tablet set (Sigma, St. Louis, MO).

3. Results

3.1. Homologous and heterologous protection following challenge with live organisms

Ferrets were fed human clinical strains of *C. jejuni* (5×10^9 CFU) and subsequently challenged 1 month later with 5×10^{10} CFU of the same Lior serotype or a different Lior serotype (Table 1). Homologous protection against signs of disease were observed when ferrets were fed either strain CGL7 (Lior 4), BT44 (Lior 9) or 81–176 (Lior 5) and then subsequently challenged with the homologous strain. Eighty to 100% protection was seen in all animals upon rechallenge. In contrast, none of the control animals remained free of disease. To determine the extent of heterologous protection that develops upon feeding *Campylobacter* to ferrets, groups of animals were first fed strain 81–176 then 1 month later challenged with either CGL7 or BT44. Similar to the homologous protection results, animals fed the Lior 5 serotype were found to be resistant to disease associated with a secondary infection when challenged with either of the two other serotypes.

Table 1
Protection against re-challenge with homologous and heterologous Lior serotypes following primary infection

Primary feeding strain	Challenge strain	No. sick/no. tested	% protected
None	81–176	5/5	0
None	CGL-7	5/5	0
None	BT44	6/6	0
81–176	81–176	0/6	100
CGL-7	CGL-7	1/6	83
BT44	BT44	0/6	100
81–176	CGL-7	2/8	75
81–176	BT44	2/6	67

3.2. Protective effect of an inactivated whole cell vaccine

A formalin-inactivated whole cell vaccine (CWC) for *C. jejuni*, strain 81–176, was used to determine whether protection seen following live challenge could be duplicated with CWC. Groups of 7 week old ferrets were fed the CWC vaccine (at a concentration of 10^9 cells), either with or without 25 μg of adjuvant. One week later the animals were fed a second dose. Control animals were either fed two doses of PBS along with 25 μg of LT_{R192G} or a single live dose (at the time of the second dose of vaccine) of 5×10^9 CFU of *C. jejuni* strain 81–176. One month following the second vaccine dose, when the ferrets were now 12 weeks of age, the animals were challenged with approximately 5×10^{10} CFU of the homologous strain. As shown in Table 2, at this concentration the level of protection was 40% with just two doses of the vaccine. Protection was not greatly improved (60%) with the addition of the adjuvant. Increasing the number of doses of the 10^9 CWC vaccine from two to four increased the level of protection to 80%. Again there was no difference between the protection with or without the adjuvant. The level of protection compared favorably to that obtained with a previous challenge with live bacteria. Since the four dose regimen with 10^9 particles of vaccine showed higher protection than two doses, ferrets were also given four oral doses of the vaccine at a concentration of 10^{10} particles per dose. The level of protection was not improved with the higher concentration of vaccine.

3.3. Cross strain protection following oral immunization with CWC

Groups of ferrets were immunized orally with either a single feeding of 5×10^9 CFU of live *C. jejuni* strain 81–176 or four doses of 10^{10} particles of CWC vaccine combined with 25 μg of LT_{R192G}. Control animals were fed four doses

Table 2
Comparison of oral dosing regimens with and without adjuvant (LT_{R192G}) for protection and IgG response following delivery of CWC vaccine

Immunization group	No. sick/no. tested	Percent protection	Median IgG reciprocal titer		
			Baseline	Pre-challenge	Post-challenge
PBS-LT_{R192G}	17/19	11	125	125	3125
One dose live strain 81–176	1/6	83	125	3125	78125
Two doses at 10^9 CWC	3/5	40	25	125	3125
Two doses at 10^9 CWC + LT_{R192G}	2/5	60	125	125	3125
Four doses at 10^9 CWC	1/5	80	125	625	78125
Four doses at 10^9 CWC + LT_{R192G}	1/6	83	125	625	78125
Four doses at 10^{10} CWC	1/9	89	125	625	78125
Four doses at 10^{10} CWC + LT_{R192G}	6/19	68	125	625	78125

of 25 μg LT_{R192G} alone. At 4 weeks post primary immunization, animals were challenged with 5×10^{10} CFU of either the homologous strain, 81–176 or the heterologous strain CGL7. Animals were then observed daily for signs of diarrhea (Table 3). Ferrets fed live 81–176 were protected against subsequent challenge with either 81–176 or the heterologous strain CGL7. The vaccine afforded demonstrable protection against live challenge with either the homologous or the heterologous strains tested. Control animals receiving only the LT_{R192G} were not significantly protected against challenge with either strain of *Campylobacter*.

3.4. Immune responses to vaccination

Serum samples were collected on the day of primary feeding/immunization, on the day of secondary challenge, and 12–19 days post-challenge. The magnitude of the serologic response to live challenge following two or four doses of vaccine was compared to the serologic response generated by a group of ferrets which was subsequently reinfected with live bacteria. The median antibody titers in the vehicle and two dose groups following challenge were found to be comparable (3,125) among these groups. In contrast, all animals receiving four vaccine doses uniformly developed antibody titers of 78,125, which is significantly greater ($p < 0.001$) than the antibody titers generated following vaccination with the vehicle or two doses of vaccine (Table 2). The magnitude of the serologic response in the group receiving the four doses followed by live challenge was comparable to that of the previously infected group challenged with live organisms. The addition of the adjuvant to the vaccine had no apparent effect on the serum titers at the given dose. Although animals given CWC had titers after challenge that were comparable with ferrets given live challenge previously, their prechallenge IgG titers were not as high as those of previously challenged animals, but was slightly higher than the titers in unprotected animals.

The IgG response was also compared in ferrets orally immunized with either four doses of the CWC vaccine or a single dose of live *C. jejuni* then challenged with the homologous or heterologous strain of *C. jejuni* (Table 3). Although the levels are low compared to those in other experiments, the titers from the group of animals fed either the live strain 81–176 of *C. jejuni* or the four doses of vaccine followed by challenge with live 81–176 were again the same. Although lower than in the homologous challenge group, similar titers were also observed when the animals were immunized with either live 81–176 or CWC then challenged with the heterologous strain, CGL-7.

Immune responses in the ferrets were also evaluated by western blotting. Analyses were done on serum from animals prior to treatment, 1 week after the fourth vaccination, immediately prior to challenge, and 1 week after challenge. No responses were seen in the placebo group until after challenge with live organisms (Fig. 1). At this time a band was seen corresponding in location to that expected for flagellar antigen. The animals immunized with CWC developed bands in the region of the 45 kDa outer membrane protein of *Campylobacter* prior to challenge. Post challenge with live organisms, these animals also showed responses to *Campy-*

Table 3
Comparison of protection and IgG response to challenge with homologous and heterologous strains of *Campylobacter*

Group	Challenge strain	No. sick/no. tested	Percent protected	Median IgG reciprocal titer		
				Baseline	Pre-challenge	Post-challenge
81–176	81–176	2/14	86	75	625	15625
81–176	CGL-7	1/13	92	125	1875	3125
Four doses at 10^{10} CWC + LT_{R192G}	81–176	7/16	56	125	625	15625
Four doses at 10^{10} CWC + LT_{R192G}	CGL-7	4/16	75	125	125	3125
Four doses LT_{R192G}	81–176	13/15	13	125	125	3125
Four doses LT_{R192G}	CGL-7	11/15	27	125	125	625

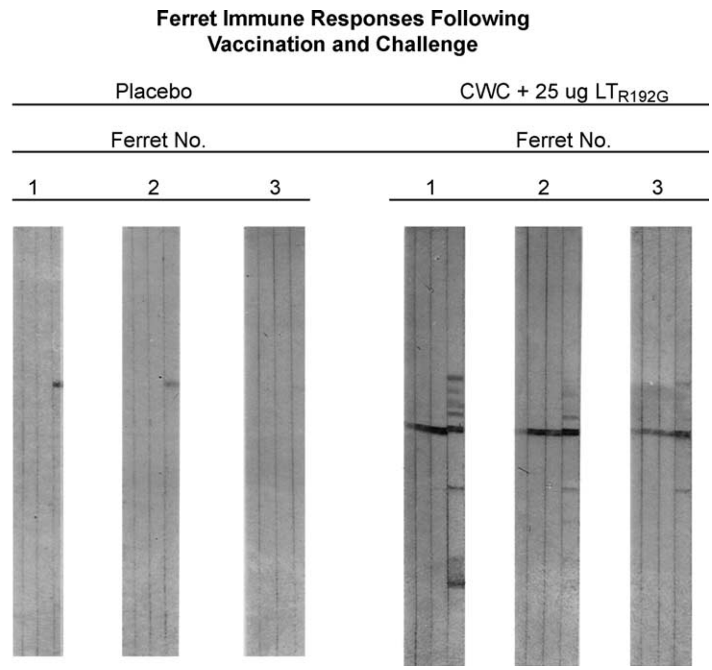

Fig. 1. Western blots of sera from ferrets given the placebo or *Campylobacter* vaccine. From left to right the samples strips were prepared from samples before treatment, 1 week after the fourth vaccination, immediately prior to challenge, and 1 week after challenge. Three representative animals are presented for each group.

lobacter antigen in the 62 kDa region seen post challenge in the placebo group.

4. Discussion

Ferrets were used to show some conservation of protection against disease induced by *Campylobacter*, a factor which could indicate the possibility of making a vaccine for humans with one strain rather than many. The animals were given a primary oral challenge with *C. jejuni* strain 81–176 (Lior 5), CGL7 (Lior 4), or BT44 (Lior 9). Upon rechallenge approximately 1 month later, homologous protection was 84% (81–176), 76% (CGL7), and 67% (BT44). Heterologous challenge of ferrets originally infected with strain 81–176 resulted in 80% protection against strain CGL7 and 67% protection against strain BT44. These data indicated that strain 81–176, the strain chosen as the vaccine strain for use in human trials, protected against disease caused by two of the major serotypes responsible for human disease as well as these two heterologous strains protected against reinfection with themselves.

An inactivated *Campylobacter* whole cell was used to demonstrate the importance of antigen dose in protection of ferrets from disease. An oral four-dose regimen of CWC (10^9 or 10^{10} cells/dose) delivered on Days 0, 3, 5, and 7 provided enhanced protection following oral homologous challenge compared to a two-dose CWC (10^9 cells/dose) regimen delivered at Days 0 and 14. The percent protection observed was 20% in PBS controls, 100% in previously infected ferrets, 50% in a two-dose CWC group, and 89% in a four-dose CWC group. These studies not only showed that protection was afforded through vaccination with sufficient inactivated whole cell vaccine, but they also showed that protection was obtained regardless of the inclusion of the adjuvant LT_{R192G}.

It was not possible to conduct extensive immunological studies in the ferrets, but the studies conducted found that live infection induces a stronger serum IgG response upon primary exposure than does the vaccine. Upon subsequent challenge, however, vaccinated animals responded with as strong a serum antibody response as did the rechallenged animals. The immunodominant antigen in ferrets given the killed vaccine is the 45 kDa major OMP; in live-challenged animals the 62 kDa flagellin antigen is dominant. This difference may reflect loss of some flagella during the fixation process. The 45 kDa OMP [24] could be an important vaccine component and could contribute to cross serotype protection. There is antigenic similarity between OMPs of different *C. jejuni* strains and OMP is also recognized by convalescent human sera [25].

The strong IgG antibody responses seen upon rechallenge of vaccinated or previously challenged animals may not be protective in themselves, but could indicate the magnitude of other unmeasured antibody responses following immunization. Anti-*Campylobacter* IgA antibodies in mucus taken from rabbits previously infected with *C. jejuni* were shown to trap the organisms and prevent attachment to underlying cells in vitro [26]. Whatever the exact nature of the protective immune responses associated with the CWC vaccine, it is clear that the vaccine offers protection which may be relatively conserved among clinically important serotypes of *Campylobacter*.

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References

[1] Stern NJ, Kazmi SU. *Canpylobacter jejuni*. In: Doyle MP, editor. Foodborne bacterial pathogens. New York: Marcel Dekker; 1989. p. 71–110.
[2] Taylor DN, Blaser MJ. *Campylobacter* infections. In: Evans AS, Brachman PS, editors. Bacterial infections of humans: epidemiology and control. 2nd ed. New York: Plenum Medical Book Co.; 1991. p. 151–72.
[3] Nachamkin I, Blaser MJ, Tompkins LS, editors. *Campylobacter jejuni*: current status and future trends. Washington, DC: American Society for Microbiology; 1992. p. 1–300.
[4] Haberberger RL, Walker RI. Prospects and problems for development of a vaccine against diarrhea caused by *Campylobacter*. Vaccine Res 1994;3:15–22.
[5] Black RE, Levine MM, Brown KH, Clements ML, Lopez de Romana G. Immunity to *Campylobacter jejuni* in man. In: Pearson AD, Skirrow MB, Lior H, Rowe BH, editors. *Campylobacter* III. London: Public Health Laboratory Service; 1985. p. 129.
[6] Black RE, Levine MM, Clements ML, Hughes JP, Blaser MJ. Experimental *Campylobacter jejuni* infection in humans. J Infect Dis 1988;157:472–9.
[7] Blaser MJ, Wells JG, Feldman RA, Pollard RA, Allen JR. *Campylobacter* enteritis in the United States: a multicenter study. Ann Intern Med 1983;98:360–5.
[8] Seattle-King County Department of Public Health. Surveillance of the flow of *Salmonella* and *Campylobacter* in a community. In: Communicable Disease Control Section. Seattle, Seattle-King County Department of Public Health, 1984.
[9] MacDonald KL, O'Leary MJ, Cohen ML, et al. *Escherichia coli* 0157:H7, an emerging gastrointestinal pathogen. Results of a one-year, prospective, population-based study. JAMA 1988;259:3567–70.
[10] Tauxe RV. Epidemiology of *Campylobacter jejuni* infections in the United States and other industrialized nations. In: Nachamkin I, Blaser MJ, Thomkins LS, editors. *Campylobacter jejuni*: current status and future trends. Washington, DC: American Society for Microbiology; 1992. p. 9–19.
[11] Calva JJ, Ruiz-Palacios GM, Lopez-Vidal AB, Ramos A, Bojalil R. Cohort study of intestinal infection with *Campylobacter* in Mexican children. Lancet 1988;1:503–6.
[12] Taylor DN, Escheverria P, Pitarangsi C, Seriwatana J, Bodhidatta L, Blaser MJ. Influence of strain characteristics and immunity on epidemiology of *Campylobacter* infections in Thailand. J Clin Microbiol 1988;26:863–8.
[13] Blaser MJ, Black RE, Duncan DJ, Amer J. *Campylobacter jejuni*-specific serum antibodies are elevated in healthy Bangladeshi children. J Clin Microbiol 1985;21:164–7.
[14] Glass RI, Stoll BJ, Huq MI, Struelens MJ, Blaser MJ, Kibriya AKG. Epidemiologic and clinical features of endemic *Campylobacter jejuni* infection in Bangladesh. J Infect Dis 1983;148:292–6.
[15] Blaser MJ, Taylor DN, Escheveria P. Immune response to *Campylobacter jejuni* in a rural community in Thailand. J Infect Dis 1986;152:249–54.
[16] Lior H, Woodward DL, Edgar JA, Laroche LJ, Gill P. Serotyping of *Campylobacter jejuni* by slide agglutination based on heat-labile antigenic factors. J Clin Microbiol 1982;15:761–8.
[17] Baqar S, Applebee LA, Bourgeois AL. Immunogenicity and protective efficacy of a prototype *Campylobacter* killed whole-cell vaccine in mice. Infect Immunol 1995;63:3731–5.
[18] Dickinson BL, Clements JD. Dissociation of *Escherichia coli* heat-labile enterotoxin adjuvanticity from ADP-ribosyl transferase activity. Infect Immunol 1995;63:1617–23.
[19] Caldwell MB, Walker RI, Stewart SD, Rogers JE. Simple adult rabbit model for *C. jejuni* enteritis. Infect Immunol 1983;42:1176–82.
[20] Pavlovskis OR, Rollins DM, Haberberger Jr RL, Green AE, Habash L, Strocko S, et al. Significance of flagella in colonization resistance of rabbits immunized with *Campylobacter* spp. Infect Immunol 1991;59:2259–64.
[21] Fox JG, Ackerman JI, Taylor N, Claps M, Murphy JC. *Campylobacter jejuni* infection in the ferret: an animal model of human campylobacteriosis. Am J Vet Res 1987;48:85–90.
[22] Bell JA, Manning DD. A domestic ferret model of immunity to *Campylobacter jejuni*-induced enteric disease. Infect Immunol 1990;58:1848–52.
[23] Bell JA, Manning DD. Evaluation of *Campylobacter jejuni* colonization of the domestic ferret intestine as a model of proliferative colitis. Am J Vet Res 1991;52:826–32.
[24] Logan SM, Trust TJ. Outer membrane characteristics of *Campylobacter jejuni*. Infect Immunol 1982;38:898–906.
[25] Walker RI, Caldwell MB, Lee EC, Guerry P, Trust TJ, Ruiz-Palacios G. Pathophysiology of *Campylobacter* enteritis. Microbiol Rev 1986;50:81–94.
[26] McSweegan E, Burr DH, Walker RI. Intestinal mucus gel and secretory antibody are barriers to *Campylobacter jejuni* adherence to INT 407 cells. Infect Immunol 1987;55:1431–5.